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This project achieved both of its stated goals. (1) The activity of single units was recorded while rats performed a divided attention task. The behavioral correlates of these units indicate three different classes: divided attention executive cells, selective attention cells, task cells. These indicate ways in which the frontal cortex is involved in attention, and provides information that can be incorporated into model systems. (2) New behavioral tasks were developed to measure reaction time in rats. These are similar to those used for testing humans, and provide animal models to assess the neuroanatomical, neuropharmacological, and electrophysiological processes involved in other kinds of attention.

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NEURAL MECHANISMS OF DIVIDED ATTENTION:

PROGRESS REPORT, NOVEMBER 15, 1989

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SUMMARY

We have made considerable progress in both components of the original proposal. The first is the analysis of single unit activity during divided attention as assessed in the temporal discrimination experiments. We have described three classes of single cells in the frontal cortex, and indicated the ways in which these are related to attentional processes. The second major area of progress is the development of new types of behavioral tasks for rats in order to assess attention, so that we can subsequently conduct recording, lesion, and neuropharmacological analyses. We have developed new procedures for measuring simple reaction time, choice reaction time and choice accuracy, and have shown that the expectations of a stimulus established from previous experience affect reaction time. Each of these projects will be described in turn.

SINGLE UNITS IN FRONTAL CORTEX HAVE ATTENTIONAL CORRELATES

The experimental procedures are identical to those outlined in the proposal. Activity of single units in the frontal cortex is recorded during a divided attention task and during unitary attention tasks. A comparison of the activity of individual cells in both conditions indicates the kinds of variables that influence the activity of these frontal cortex cells. A particularly important variable is the presence of a demand for divided attention. These data indicate that cells in the frontal cortex are critical for effective divided attention, supporting conclusions drawn from previous studies examining the behavioral effects of lesions in frontal cortex. Importantly, these results provide new information about the ways in which single nerve cells in the frontal cortex mediate the processes of divided attention.

The experimental procedure is based on variations of a signalled fixed interval schedule of reinforcement as described in the proposal. For each training trial, a signal was turned on. At the end of a fixed interval of time, food was provided for the first response. Two signals, each associated with a different fixed interval schedule, were used for the training trials. One fixed interval was 10 seconds, the other fixed interval was 40 seconds.

Probe trials presented each stimulus for an extended period of time, and provided no reinforcement for any response. Consequently, these probe trials gave the rat no external information indicating when the fixed interval was completed. The peak time was defined as the time during which the response rate was greatest during each probe trial.

Each simple probe trial presented one stimulus for an extended period of time, and provided no reinforcement for any

response. The peak time during a simple probe trial occurred at the time after the onset of the stimulus when food was normally available in the training trials. This value of the peak time indicates that the rats had learned to time each stimulus individually and identify the time at which food was usually available.

Each compound probe trial presented both stimuli. The long stimulus (the stimulus associated with the long fixed interval schedule of reinforcement) was presented first. Following a short but variable interval of time, the short stimulus (the stimulus associated with the short fixed interval schedule of reinforcement) was presented. During these compound trials, the optimal strategy for the rat was to time each stimulus simultaneously, producing a peak time at the appropriate interval following the onset of each stimulus. Because both stimuli were present simultaneously on compound probe trials, these trials required divided attention.

As described in more detail in the copy of the poster from Society For Neuroscience (attached to this report), the frontal cortex contained three classes of cells. Each of these will be described in turn.

Divided attention executive cells responded more in compound probe trials than would be predicted from the sum of their responses in both simple probe trials. Thus, these cells had a differential increase in the rate of activity when divided attention was required. This differential responding in compound probe trials, as compared to simple probe trials, suggests that these cells performed an executive function, distributing attention between the two different tasks. This pattern of activity is consistent with other theoretical analyses of the functions of the frontal cortex which emphasize its role in executive, planning functions. The data are also consistent with the results of the previous lesion experiments; lesions of the frontal cortex produced an impairment in divided attention, characterized by an inability to time each stimulus simultaneously. Together, these data suggest that this differential activation of the frontal cortex is required for successful divided attention, indicating that the frontal cortex itself is responsible for dividing attention, or that it responds to the activation of some other brain area. In any case, it is a critical link that is activated when divided attention is required, and is necessary for successful allocation of attention between simultaneous tasks.

Selective attention cells responded to each stimulus when presented alone in a simple probe trial, but responded to only one stimulus when both were presented together in a compound probe trial. This pattern of activity indicates that the cells were able to respond to each stimulus, but selected only one

stimulus when both were present. These cells must either produce selective attention, or be downstream from other cells that are responsible for the selection. In either case, these cells respond differentially during the requirement for divided attention, in compound trials, as compared to the absence of this requirement, in simple trials.

Each task specific cell responded to only one stimulus, and the response was the same in both simple trials and compound trials. The response characteristics of these cells were unaffected by the requirement for divided attention, indicating that the activity of these cells reflects the demands of that single task regardless of what other tasks might be involved.

Together, these three types of behavioral correlates provide important evidence that single units in the frontal cortex are involved in divided attention, and they begin to provide the kinds of information that are necessary to produce a neurocomputational model of the attentional mechanisms in the frontal cortex.

REACTION TIME EXPERIMENTS

We have also made considerable progress developing experimental procedures to assess reaction time. These procedures are important because they allow us to make better comparisons with the procedures used in experiments with humans, and because they will provide us a better assessment of attentional processes in rats so that the electrophysiological, neuropharmacological, and neuroanatomical mechanisms of attention can be examined more thoroughly.

One set of experimental procedures has already been established. These allow measurements of simple reaction time, choice reaction time, choice accuracy, and the effects of expectation on reaction time and choice accuracy.

For the task, the rat stands comfortably on his hind legs, placing each of his forepaws on a lever. A water tube, located above and between the two levers, provides reinforcement. The tube is positioned so the rat does not have to move in order to obtain reinforcement, and can remain standing with his forepaws on the levers. Rats find this position quite natural (it is similar to that used when rearing and investigating), and respond accurately in the task for as long as we wish to test them, up to 1 hour.

For simple reaction time, one stimulus (a light or a tone) is presented on all trials, and one response (lifting one lever) is correct on all trials. Consequently, whenever a stimulus is presented, the rat should respond as quickly as possible. Reaction times are typically about 250 milliseconds.

For choice reaction time, one of two stimuli can be presented for each trial, and the rat responds differently for these. For example, following a light, a response on the left lever may be correct, whereas, following a tone, a response on the right lever is correct. Rats learn this task quickly (about 3 weeks) and perform accurately. Reaction times in this choice task are similar to those in the simple reaction time task. This similarity was unexpected, and we are currently investigating the reasons for it. One obvious explanation is the use of stimuli and responses that are highly differentiated. The two stimuli are in different modalities, and the two responses are made from different forepaws. If the stimulus-response independence of these two tasks is responsible for the rapid reaction times in the choice reaction time task, then reducing this independence should produce a differential increase in choice reaction time. The two different stimuli can be presented in the same modality, and the two different responses can be required from the same forepaw. Such an arrangement should reduce independence, increase interference, and result in a differential increase in choice reaction time as compared to simple reaction time.

Expectancy is operationally defined as the probability of a stimulus occurring on a given trial. Expectancy was manipulated by varying the relative ratio of presentation of each of the two stimuli in the choice reaction time task: 90%/10%, 50%/50%, 10%/90%. These changes in the ratio of the two stimuli produced an expectancy effect on reaction time. Reaction time to the high probability stimulus (90% of the trials) was shorter than reaction time to the low probability stimulus (10% of the trials). This differential reaction time indicates that rats were allocating their attention differentially as a function of their expectancy, which was determined by previous experience with the stimuli.

PLANNED EXPERIMENTS

Data Analysis For The Divided Attention Temporal Discrimination Experiments

We are continuing to develop effective ways of analyzing the results from the divided attention procedures, and conducting those analyses on the data that we have already obtained. We have single unit recordings for a total of 53 cells in the frontal cortex, and are continuing to analyze them in order to determine the ways in which they respond in the divided attention trials as compared to the unitary attention trials. We hope to have these analyses finished early in 1990.

Acquisition Of Further Data From The Divided Attention Temporal Discrimination Task

We have trained an additional group of rats in this divided attention procedure, and are in the process of obtaining data from them using the same procedures that we used with the previous groups. These additional data are necessary to obtain an accurate sample of the kinds of cells that respond during these attentional tasks. We expect that experimentation for this group will end in the middle of 1990, and that we will have completed data analysis for it shortly thereafter. Because we are proceeding with data analysis and interpretation at the same time that we are acquiring these new data, the entire project should be completed soon after the additional groups have completed testing, and we intend to submit a manuscript for publication as soon as possible.

Reaction Time Experiments

We are continuing to test rats in the reaction time experiments described above, and intend to test the effects of frontal cortex lesions in them. If the frontal cortex is involved in divided attention, then lesions of it should differentially affect reaction time in the choice reaction time tasks as compared to the simple reaction time task, and should disrupt the expectancy effect resulting from changes in probability of stimulus presentation. If these results occur, then we will consider recording from single units in this choice reaction time task.

As a result of our current experience in training rats in reaction time tasks, we are now in the process of developing even more effective procedures to do this testing. Of particular importance is the continued development of an apparatus that allows us to provide equivalent tests of attentional processes in rats and humans. The apparatus is being modified so that several different responses can be made by the rat with each forelimb, and several different stimuli can be presented in each modality. Procedural changes are being implemented that will allow us to test the effects of stimulus onset asynchrony. These are all important steps in developing the procedures outlined in our proposal. We expect to have preliminary data on their effectiveness early in 1990, and will make a decision about our experimental strategy then. If these new tasks are more effective than our present ones, then we will concentrate our neural analyses on them. If some unexpected difficulties arise, however, we will pursue our neural analyses with the current behavioral tasks.

CONCLUSIONS

This project has been successful in both of its major proposed components. Single unit activity in the frontal cortex has significant correlates with attentional demands, and these data will begin to provide the critical information for modelling the neural mechanisms involved in divided attention. The new behavioral testing procedures, designed to obtain measurements of reaction time as well measurements of choice accuracy, continue to show their appropriateness for assessing the neural mechanisms of attention in rats. The information that we have obtained so far is useful in its own right, and provides assurance that the future goals of this project can be pursued effectively.

FRONTAL CORTICAL CELLS OF RATS ARE ACTIVATED IN A DIVIDED ATTENTION TASK. K. Pang, D. Olton and H. Egeth. Dept. of Psychology, The Johns Hopkins University, Baltimore, MD 21218.

The frontal cortex (FC) is critically involved in divided attention. FC lesions in rats disrupt divided attention, while leaving focussed attention intact. In the present study, the activity of FC neurons was examined in a temporal discrimination task. Rats were trained to two stimuli (light and tone), each associated with a different fixed interval. Focussed attention trials (single stimulus presented) and divided attention trials (two stimuli presented) were given randomly within a session. Recording electrodes were implanted into the FC in trained rats. Extracellular recordings of FC cells were taken while the rat was performing the discrimination task. Neuronal activity was correlated with the behavioral performance. Some cells cells had divided attention correlates; these cells selectively increased their firing rate to the second stimulus in divided attention trials, but not to the same stimulus in focussed attention trials. Several firing patterns were observed, suggesting that FC neurons may code different aspects of divided attention. The remaining cells had more complicated firing patterns, which seem to involve motor responses; these cells increased their firing rate with increasing bar press rate in both focussed and divided attention trials. The data provide evidence that the frontal cortex is involved in both divided attention and motor responses.

METHODS

Rats were trained in a peak interval procedure with two stimuli. The two stimuli were a light and a tone. Each stimulus signalled either a short or a long fixed interval which remains constant for a rat. Trials were divided into reward and probe trials. On **reward trials**, the first lever press after the fixed interval was rewarded and the stimulus turned off. On **probe trials**, no reward was given to the rat and the stimulus remained on for the duration of the trial (3 x fixed interval). Probe trials were randomly interspersed with reward trials. After acquisition of the task, rats were implanted with electrodes for electrophysiological recording from the frontal cortex. Rats were re-tested after surgery with behavioral and electrophysiological data accumulated on probe trials. Each cell was also tested in a "No-task" condition. In the "No-task" condition, stimuli were present to the rat as in the normal condition, but the animal was not allowed to lever press and was not rewarded. The "No-task" condition was used to assess whether neurons of the frontal cortex were responding to the physical properties of the stimuli.

SIMPLE SHORT TRIAL

Long stimulus

Short stimulus

SIMPLE LONG TRIAL

Long stimulus

Short stimulus

COMPOUND TRIAL

Long stimulus

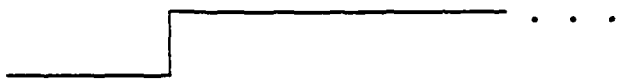
Short stimulus

Three types of trials were randomly presented to the animal (see figure above). A short stimulus (10 seconds fixed interval) was presented alone on **simple short trials**. A long stimulus (20 or 40 seconds fixed interval, but constant for a rat) was presented alone on **simple long trials**. Both stimuli were presented on **compound trials**; the long stimulus is presented first, followed by the short stimulus. Divided attention was required on compound trials because the rat timed both stimuli simultaneously. Unitary attention was used on simple trials because the rat timed a single stimulus.

Peri-event time histograms (PETHs) were constructed for unit activity occurring around the onset of a stimulus (see table below). Each bin of the PETH is expressed as the percent change of the average baseline. The formula was as follows ([post-event bin - pre-event bin average]/pre-event bin average)*100.

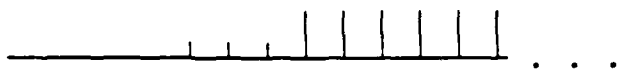
PETH	TRIAL	ALIGNED AT ONSET OF
Simple short	Simple short	Short stimulus
Simple long	Simple long	Long stimulus
Compound short	Compound	Short stimulus
Compound long	Compound	Long stimulus

COMPOUND TRIAL PETH



Compound Trial - Long Stimulus

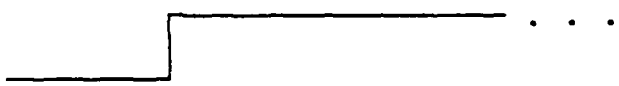
Compound Trial - Short Stimulus



Compound Trial PETH

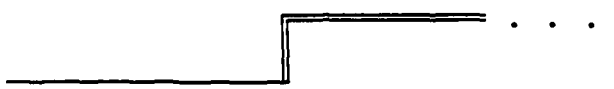
6 seconds

SUMMED SIMPLE TRIAL PETH

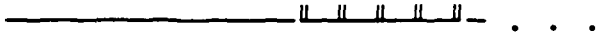


Simple Trial - Long Stimulus

Simple Trial PETH - Long Stimulus

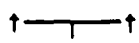


Simple Trial - Short Stimulus



Simple Trial PETH - Short Stimulus

SUMMED SIMPLE TRIAL PETH

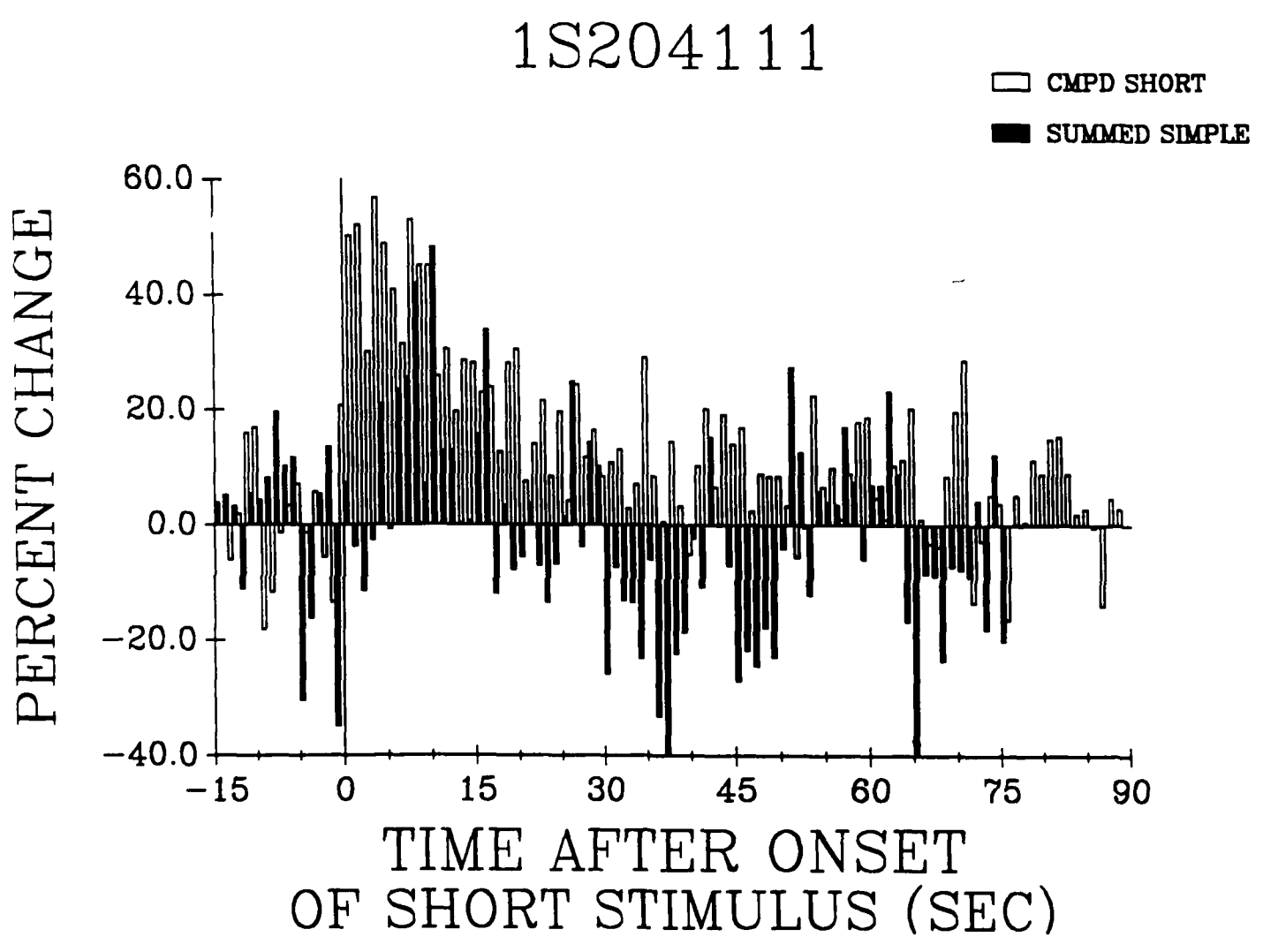


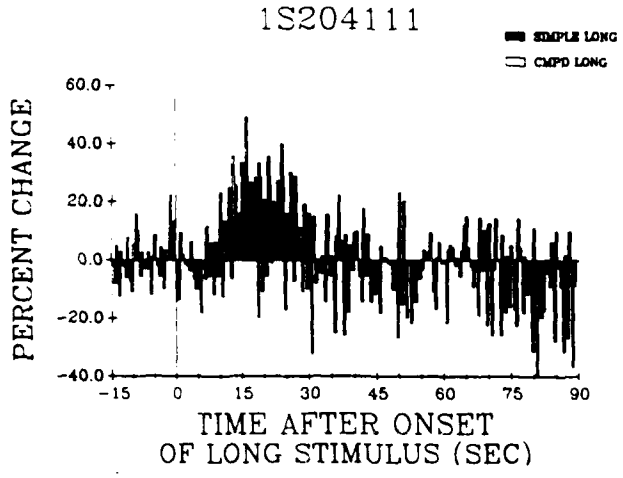
6 seconds

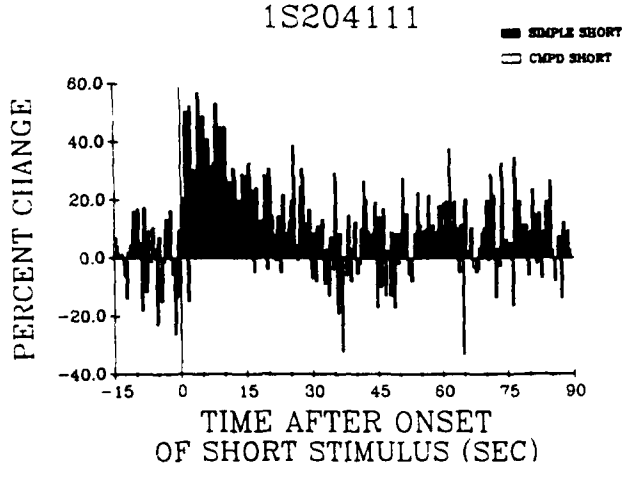
The neuronal activity on compound trials were compared to the summed activity on simple trials. Two stimuli were presented during compound trials, while a single stimulus was presented during simple trials. Therefore, a difference between firing rates on simple and compound trials may occur because the unit responded to both stimuli on compound trials, but could only respond to one stimulus on simple trials. In order to examine this possibility, PETHs from simple short and simple long trial were summed and compared to the PETHs from compound trials. For the summed simple trial PETH, the simple short PETH was offset from the simple long PETH by an amount which equalled the time between onset of short and long stimulus in each compound trial (see figure above).

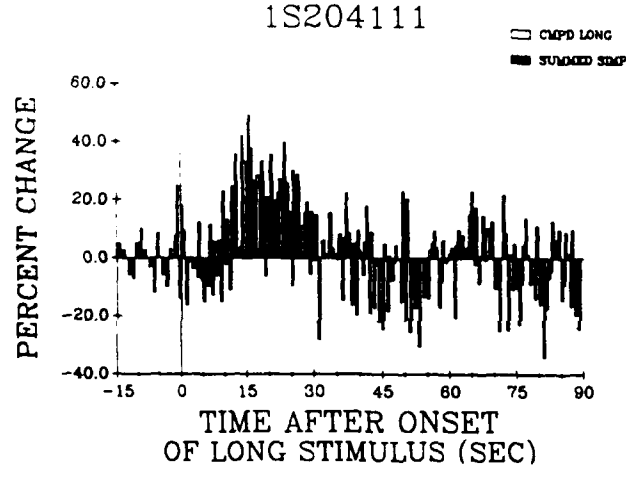
Divided Attention Executive Cells:

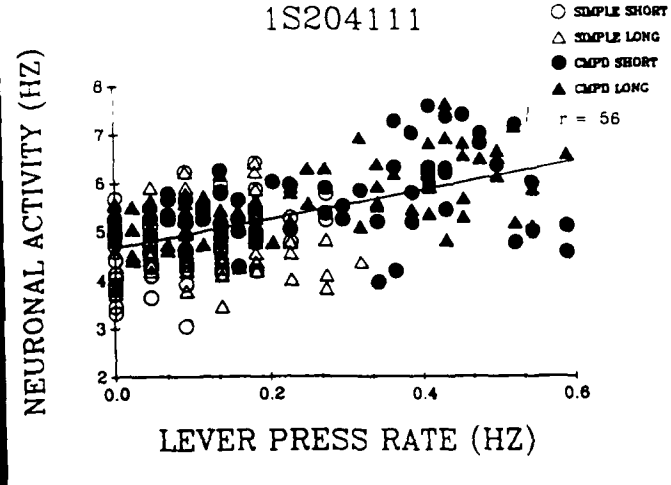
Response in compound trials was <u>GREATER</u> than the summed response in simple trials.







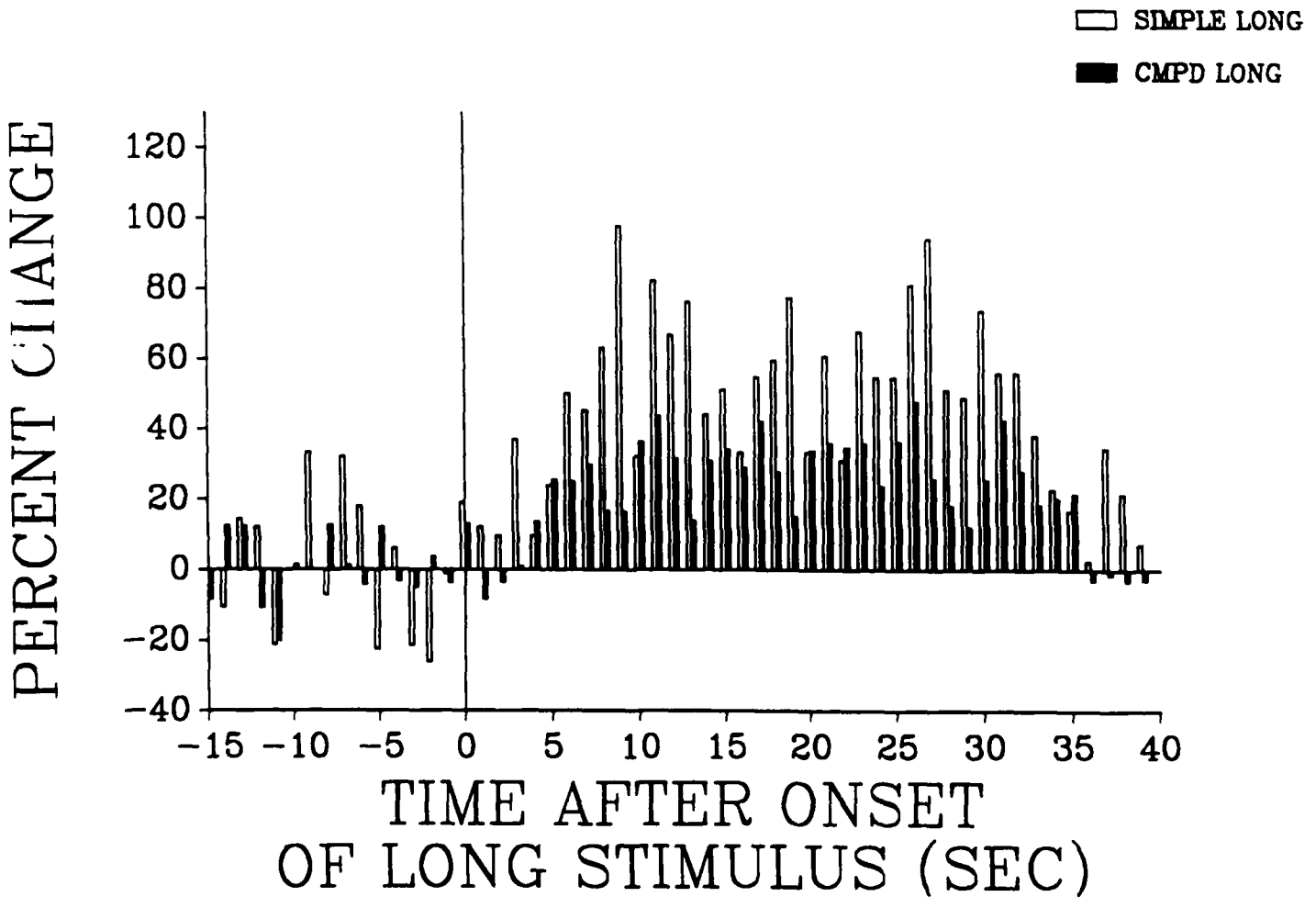


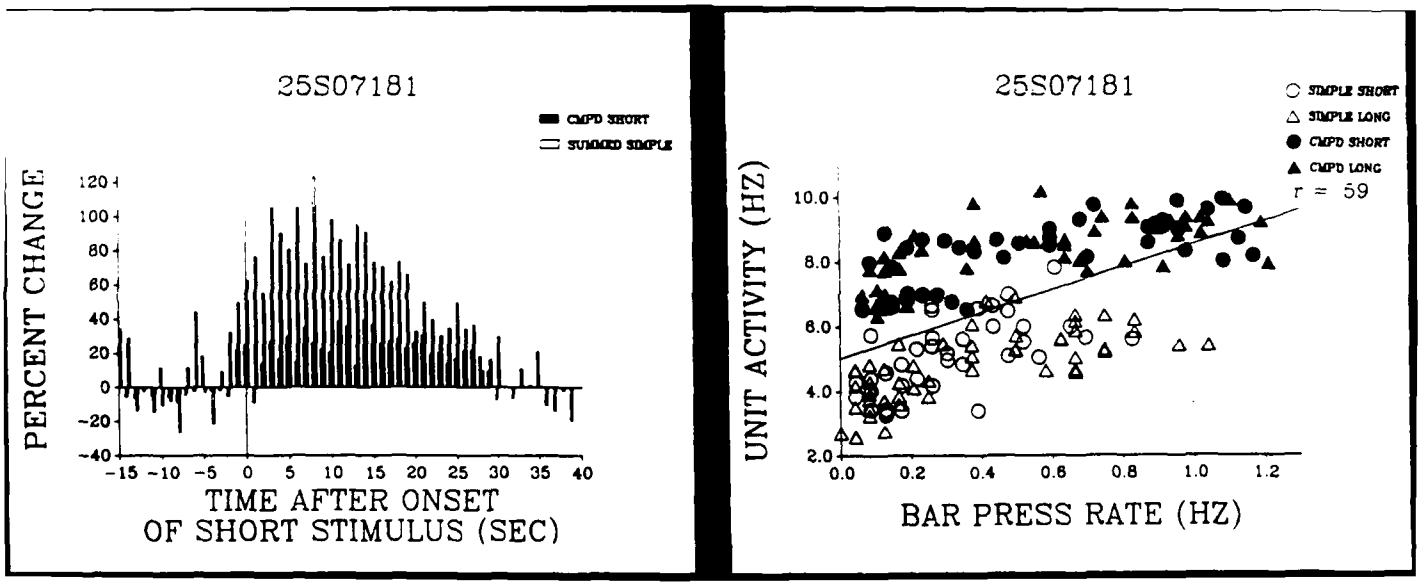


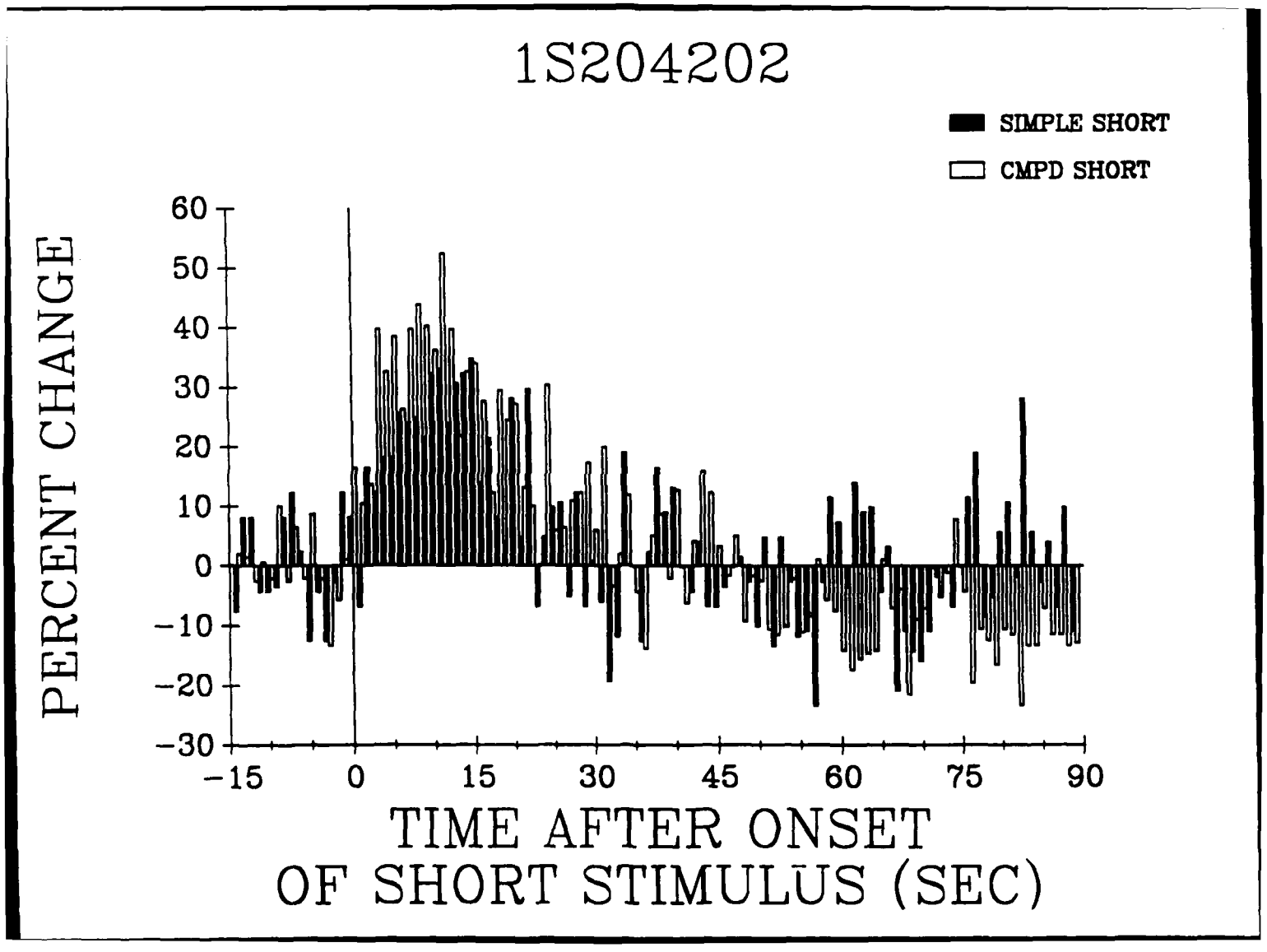
DIVIDED ATTENTION EXECUTIVE CELLS: Examples of the firing pattern from an executive cell are shown for three types of trials. The first ten seconds of the compound short stimulus was the period when both stimuli were timed simultaneously and divided attention was required. During this period, the neuronal activity of executive cells was greater than the summed activity of simple long and simple short trials. **The neuronal activity of executive cells was dependent on the utilization of divided attention. The function of these cells in a divided attention task may be to maintain the identity of the two stimuli.**

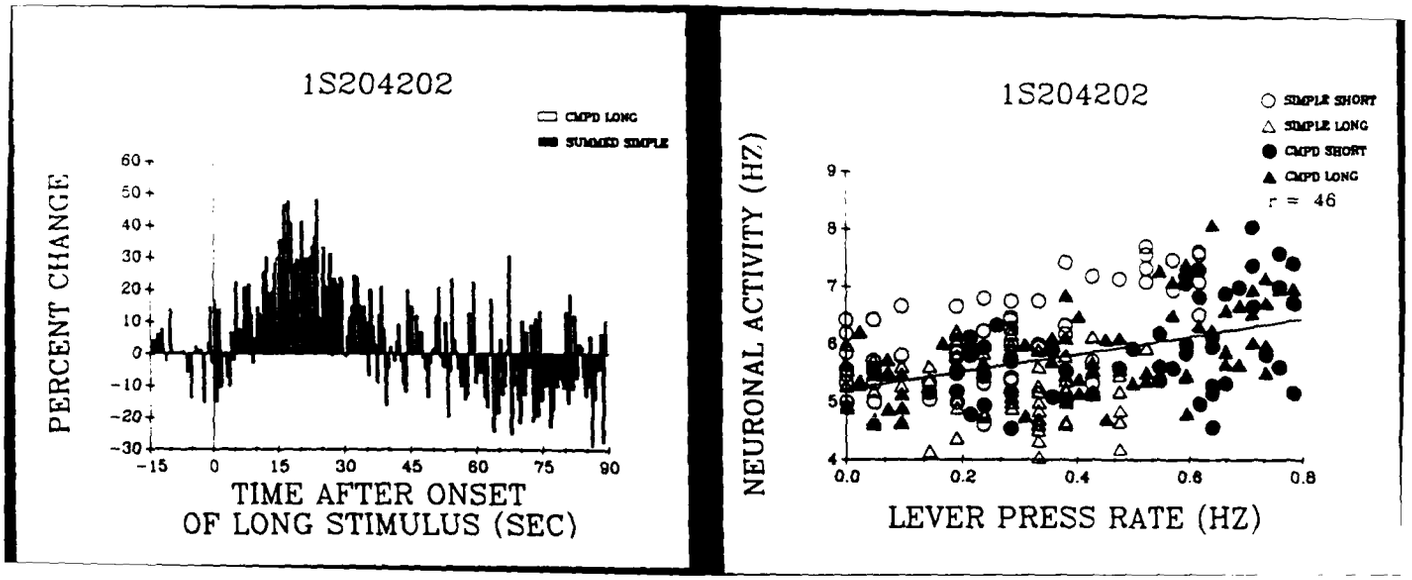
Selective Attention Cells: Response in compound trials was <u>SIMILAR</u> to the response in a simple trial. Response was seen in <u>both</u> simple trials.

25S07181

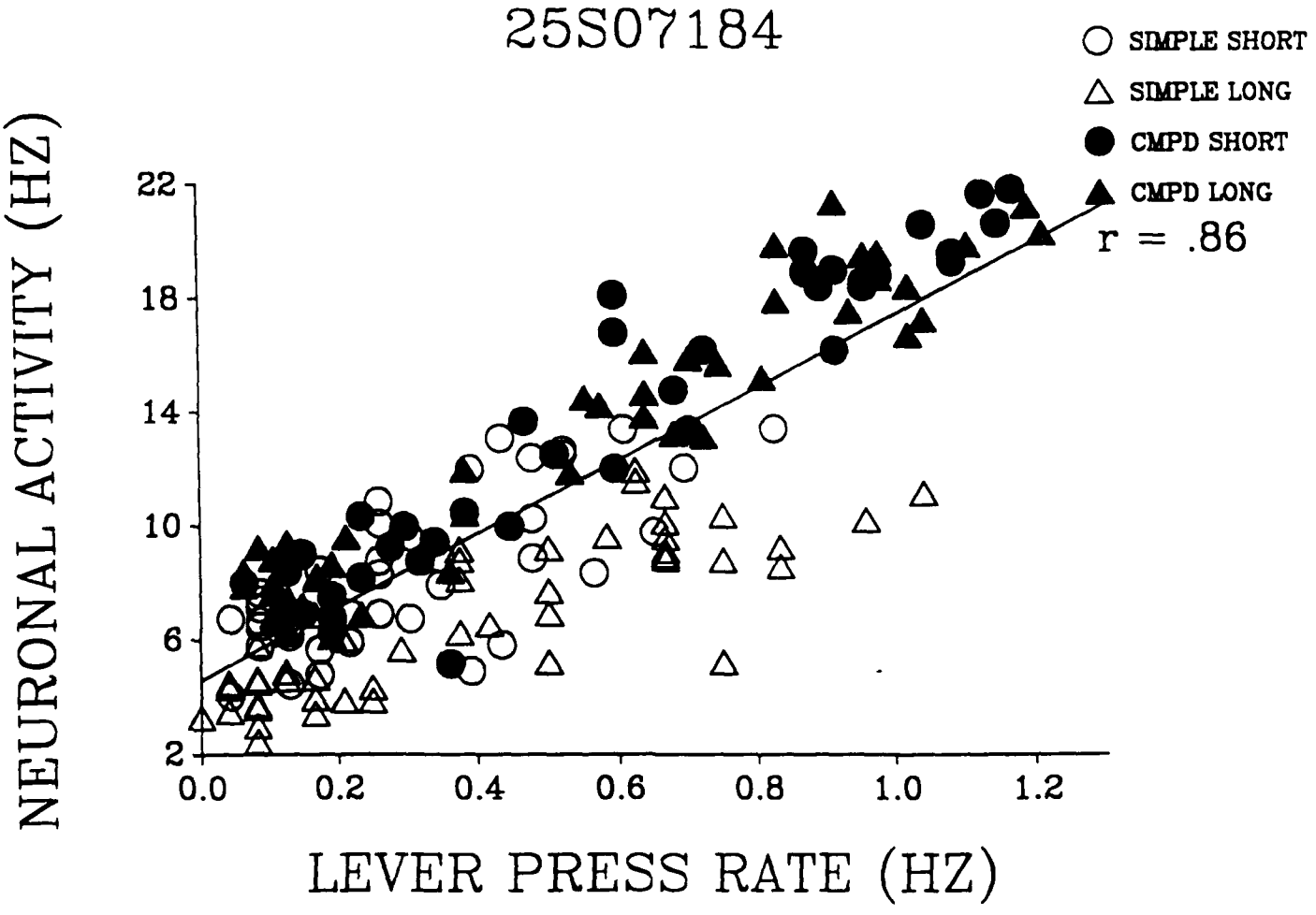


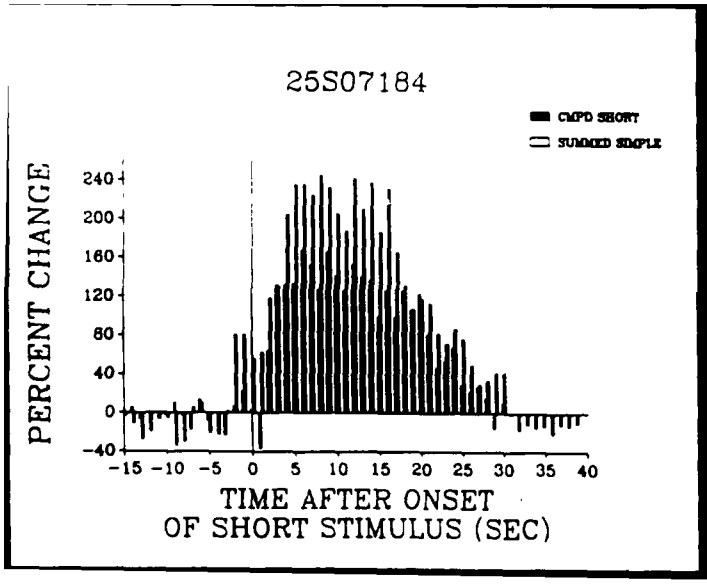

25S07181
CMPD SHORT
SUMMED SIMPLE
PERCENT CHANGE
120
100
80
60
40
20
0
-20
-40
-15 -10 -5 0 5 10 15 20 25 30 35 40
TIME AFTER ONSET
OF SHORT STIMULUS (SEC)
25S07181
SIMPLE SHORT
SIMPLE LONG
CMPD SHORT
CMPD LONG
r = 59
UNIT ACTIVITY (HZ)
10.0
8.0
6.0
4.0
2.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2
BAR PRESS RATE (HZ)

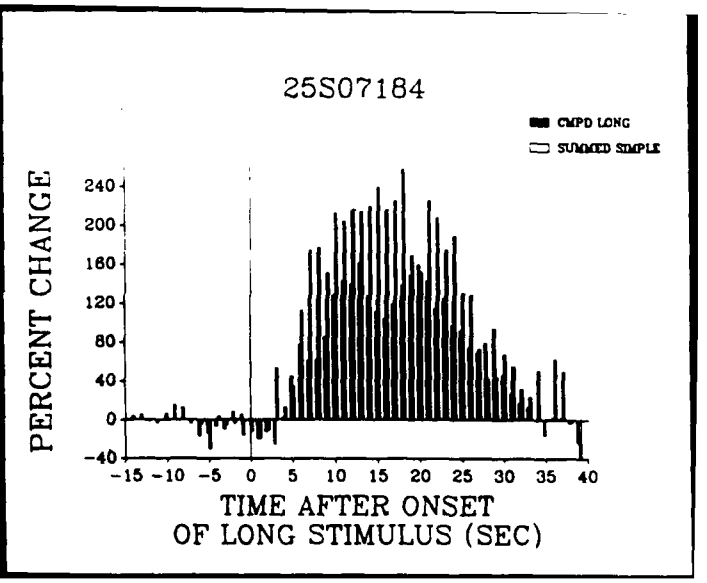

1S204202
SIMPLE SHORT
CMPD SHORT
PERCENT CHANGE
60
50
40
30
20
10
0
−10
−20
−30
−15
0
15
30
45
60
75
90
TIME AFTER ONSET
OF SHORT STIMULUS (SEC)


1S204202
CMPD LONG
SUMMED SIMPLE
PERCENT CHANGE
60
50
40
30
20
10
0
-10
-20
-30
-15
0
15
30
45
60
75
90
TIME AFTER ONSET
OF LONG STIMULUS (SEC)
1S204202
SIMPLE SHORT
SIMPLE LONG
CMPD SHORT
CMPD LONG
r = .46
NEURONAL ACTIVITY (HZ)
9
8
7
6
5
4
0.0
0.2
0.4
0.6
0.8
LEVER PRESS RATE (HZ)

Response Cells: **Firing rates correlated with the rate of lever pressing.**




25S07184
CMPD SHORT
SUMMED SIMPLE
PERCENT CHANGE
240
200
160
120
80
40
0
-40
-15 -10 -5 0 5 10 15 20 25 30 35 40
TIME AFTER ONSET
OF SHORT STIMULUS (SEC)


25S07184
CMPD LONG
SUMMED SIMPLE
PERCENT CHANGE
240
200
160
120
80
40
0
-40
-15 -10 -5 0 5 10 15 20 25 30 35 40
TIME AFTER ONSET
OF LONG STIMULUS (SEC)

Classification of cells were based on the firing patterns in the simple and compound trials. Mathematical descriptions of the neuronal activity near the time of reinforcement are given below.

Divided Attention Executive Cells:

$$ACT_{CM}(t_S,t_L) > ACT_{SS}(t_S) + ACT_{SL}(t_L)$$

General Processing Cells:

$$ACT_{CM}(t_S,t_L) = ACT_{SS}(t_S) + ACT_{SL}(t_L)$$

Selective Attention Cells:

Given the cell responds to BOTH simple stimuli,

$$ACT_{CM}(t_S,t_L) = ACT_{SS}(t_S) \text{ OR } ACT_{SL}(t_L)$$

Task Specific Cells:

Given the cell responds to ONE simple stimulus,

$$ACT_{CM}(t_S,t_L) = ACT_{SS}(t_S) \text{ OR } ACT_{SL}(t_L)$$

Response Cells:

$$ACT_{CM}(t_S,t_L) = k * R_{LP}$$

$ACT_{CM}( )$ = activity on compound trials

$ACT_{SS}( )$ = activity on simple short trials

$ACT_{SL}( )$ = activity on simple long trials

t_s = time after onset of short stimulus

t_L = time after onset of long stimulus

R_{LP} = rate of lever pressing

k = constant

SUMMARY

Four types of behavioral correlates were found for cells in the frontal cortex of rats.

1. Divided attention executive cells had neuronal activities which depend on the use of divided attention. The function of executive cells may be to separate multiple processes which occur simultaneously in a divided attention task.
2. Selective attention cells responded to a single stimulus during the divided attention task. The function of selective attention cells may be to execute a single process in a divided attention task. Alternatively, these cells may have a critical function in selective attention tasks.
3. Task selective cells responded to a single stimulus during both simple trials and compound trials. The function of these cells may be to process a single task, regardless of whether unitary and divided attention is required.
4. Response cells alter their firing rates in relation to the rate of lever pressing.

Data from lesion and electrophysiological studies provide evidence for the important role of the frontal cortex in divided attention. The electrophysiological data point to an additional role of the frontal cortex in selective attention.